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Space–environment effects on optical cables

R. Hartmayer, S. Jackson and A, R. Johnston

Jet Propulsion I Amatory
California institute of Technology
Pasadena, California 91109

ABSTRACT

Results obtained from the 1 .ong-Durat ion Exposure Facilit y (LDEF) JPL fiber optics experiment, which remained in low-earth orbit for 5 3/4 years, are discussed in order to illu strate the effects of the adverse space environment on fiber optic cables. The results of tests performed on the ten fiber optic cable samples, flown on the LDEF, arc then compared to data obtained from similar laboratory tests performed on currently available fiber optic cables. The effects of radiation exposure, temperature cycling, polymer aging, and micrometeoroid impacts on fiberoptic cables applied in space arc discussed. Overall, it seems that current commerciall y available fiber cables could bc used for space missions, if kept in a controlled environment. Improvements in purity of silica glass, in buffer matings, and in cabling materials arc already visible in the new generation of fiber cables, bringing it one step closer to the ultimate "space qualified" fiber cable.

1. INTRODUCTION

Fiber optic data links will play an important role in future space missions. A FDDI fiber optic network, operating at 125 Mb/s will bc an integral part of the baseline space-station, whereas fiberoptic data busses, operating in the Gb/s data rate regime, arc being considered for interconnecting high–bandwidth instruments on military and scientific space deployed platforms.

The level of confidence in the usc of optical fiber technology in future space missions, has recently increased as a result of the data obtained from several fiber optic experiments, flown aboard the Long-Duration Exposure Facility (1 .DEF)[1]. The purpose of the LDEF fiber optic exposure experiments was to study the effects of the low earth-orbit space environment on optical fibs cable rind connector samples[2]. The JPL experiment, which included ten optical fiber cables, provided data on the effects of ionizing radiation, periodic temperature cycling, polymer aging, mechanical deterioration of the packaging, contamination of connectors, and micrometeoroid impacts on the fiber cables[3,4]. The JPL fiber optic exposure experiment was initiated in 1975, with the final fiber cable selection taking place in 1982. The experiment tray was launched on board the space shuttle in April, 1984. It was recovered 68 months later, in January of 1990, with the post- flight anal ysis commencing in April, 1990. The total mission duration was 5 3/4 years, in which the LDEF was in near circular low-earth orbit, starting at an altitude of 420 km and ending at 290 km.

In this paper wc will summarize the results of the LDEF fiber optic cable post--flight analysis, and describe initial results of radial ion and temperature response tests performed on currently available optical fiber cable samples. Wc start by describing the fiber optic cables. The following sections describe the experimental setup and summarize the experimental data, A discussion of the results and conclusions follow.

2. FIBER CABLE SAMPLES

A total of ten different fiber optic cable samples, mostly off- the- shelf products in the early 1980's, were, flown as part of the JPL LDEF experiment. Four samples were mounted on the surface of the experiment tray, whereas the remaining six cables were placed inside. the tray, shielded behind aluminum plates. All the major fiber types, such as plastic-clad, large- core, graded index and single- mode, were represented. An identical control sample was kept at JPL for post-flight comparisons, Table 1 lists the ten fiber cable.s including pertinent parameters on their construction and a variety of nominal performance parameters, External fiber cable samples arc identified by the letter 'P', while the internal samples arc identified by the letter 'C'.

In addition, three currently available, multi- mode, fiber optic cable samples were tested as part of this work and arc listed in Table 2. The first fiber cable sample, 'N- 1', was chosen because it is the modern off-the- shelf equivalent of the 'P- 1' fiber cable, which exhibited the least temperature and radiation related degradation of all ten cable samples, flown on LDEF. The 'N-2' sample is a standard fiber, placed inside a space qualified cable. The 'N–3' sample is a radiation-hardened, temperature resistant, fiber placed inside a space qualified cable. These three fiber cable samples, we believe, represent a cross--section of the choices currently available to the spacecraft fiber optic system designer.

3. TEMPERATURE EFFECTS

Fiber optic cables deployed in space arc subjected to temperature extremes. In low- earth orbit, the LDEF fibers went through a complete hot-cold cycle within roughly 90 minutes, resulting in a total of over 33,000 such cycles during the 5 3/4 year LDEF mission. For externally deployed fibers, temperature fluctuations in space could conceivably range from –150° C to + 150° C. On the other hand, external fibers with some shielding could experience much smaller temperature fluctuations, from -30° C to +70° C. For fibers located internally the expected temperature fluctuations arc reduced even further, extending from - 10°C to +40° C. The cold temperature extreme usually has a more significant impact on the performance of fiber optic cables, mainly duc to the fact that the fiber loss typically increases appreciably at these temperatures. The main cause for the attenuation increase is microbending, which causes coupling between guided and radiated modes[5]. in general, microbending can be traced to the fiber- buffer interface and results from: 1) a compressive strain in the fiber, duc to the difference in coefficient of linear expansion between the fiber and the. buffer, and 2) the crystallization, or phase change, of the polymer buffer coating.

In order to evaluate the effects of temperature on the cabled fiber samples, the *change in* the optical fibers' attenuation was recorded as a function of temperature. The fiber were inserted in a computer controlled temperature chamber, and the temperature was cycled three times from room temperature., up to + 70" C, down to --55 °C and back up to room temperature, over a twelve hour period, The fiber cable was kept at the two extreme temperatures for 30 minutes. Both fiber ends were left outside of the temperature chamber, and were connected to a LED source and to an optical power meter. A second input from the LED to the optical power meter, via a fiberoptic splitter, allowed compensation for the output power fluctuations of the light source. The light source, the splitter and the optical detector heads were. all placed inside a temperature controlled box, and their temperature was maintained at 32° C. This procedure decoupled the test setup from fluctuations in room temperature. The temperature and light transmission data were recorded every five minutes using a personal computer based data acquisition system. The measurements were taken at both 820 nm and 1300 nm wavelengths.

The attenuation changes in all fibers exhibited a hysteresis type behavior, where the attenuation measured during the cooling cycle did not correspond to the attenuation measured during the heating cycle. Overall, most fiber cable.s experienced an increase in loss with decreasing temperature. Table. 3 shows the, temperature induced changes in attenuation, extrapolated in dB/km. Among the LDEF fibers, the 'P- 1' sample exhibited the lowest overall change with temperature, an increase of about 2 dB/km at the low temperature extreme. Most LDEF samples exhibited a much larger increase in attenuation at the low temperature extreme. The 'C- 1' cable, for example, had an attenuation increase of about 17 dB/km at the low temperature extreme, while its attenuation remained almost unchanged at the. higher temperatures. The change in attenuation in the current fiber samples was minute compared to the LDEF fiber samples. Surprisingly, two of the three current fiber samples exhibited a decrease in attenuation at the low temperature extreme, while the attenuation increased at the high temperature extreme. Figures 1 and 2 show the plots of attenuation versus temperature for the '1'–1' and 'C- 1' LDEF fiber cables, whereas Figures 3, 4 and 5 show the same plot for the current fiber cable samples. On all graphs, the vertical axis indicates the *change* in the fibers' attenuation at a particular temperature, in dB/km, with respect to the fibers' attenuation at room temperature.

4. RADIATION EFFECTS

In a space environment, fiber optic cables arc exposed to ionizing radiation comprised primarily of clectron and proton radiation. While the first type of radiation contributes to the total dose damage, the second type also causes damage duc to atom displacement in the material itself. When exposed to radiation, the transmissive properties of optical fibers arc compromised by the formation of color centers in the fiber core, formed when electrons or holes generated by the radiation are trapped at defects or impurities in the glass. Usually, defects already exist in the glass prior to exposure, and are only increasing in number after radiation exposure. Although the rate of defect creat ion in the fiber is not temperature dependent, the rate at which these defects trap the charge, thereby faming color centers, is strongly temperature dependent[6]. Photobleaching, a process which causes trapped charges to recombine via photoexcitation, enhances the recovery of radiation induced loss. In general, an increase in the fibers' attenuation and a slowdown in the recovery process occur at low temperatures.

Materials added to the glass during the fiber manufacturing process, arc also known to degrade the fibers' performance when exposed to radiation[7,8,9]. Germanium, added to fiber cores in order to increase the index of refraction, usually dominates the radiation response of the fiber. Because the trapping sites associated with Ge arc relatively shallow, Ge doped fibers recover rapidly, Phosphorus, a dopant somct imcs added to facilitate the fabrication process, greatl y increases the long-term radiation sensitivity of fibers. The OH content of the fiber and another dopant, arsenic, used in fiber preforms, arc also known to in fluence the fibers' radiation response.

The externally mounted fiber coils on LDEF experienced approximately a 1 krad total mission dose, at the fiber, calculated from dose versus shielding depth curves[10]. The dose incident on the cable jacket was around onc order of magnitude larger. The internal samples, shielded by 4.8 mm thick aluminum plates, experienced around 200 rads. Our radiation exposure tests consisted of exposing the ten LDEF control samples and the three current fiber cable samples to a Co^{60} gamma-ray source, inducing a total dose of approximately 2 krads and 5 krads, respectively. Although the procedures for transient radiation testing of optical f ibers[11] were followed, the dose rate was decreased and the du ration of exposure was increased because of our interest in the long-term residual loss increment. The measurement setup was similar to the onc described in the previous section. All measurements were taken at room temperat urc with a 820am LED light source. The optical power going through the f ibcr was about 20 µW, and the light at the fiber output was monitored continuously.

Table 3 lists the radiat ion induced peak attenuation at the end of the irradiation process, as well as the residual attenuation, at 10^{+5} seconds. Figures 6 and 7 show plots of attenuation versus time for two of the LDEF samples. A fcw LDEF fibers, such as the '1'–1' sample, recovered fairly rapidly, and reached their final residual attenuation witbin 24 hours after the radiation exposure occurred. The 'C–1' fiber exhibited a very gradual annealing process, spot-measured over several months, and retained a relat ively high residual attenuation. This behavior was typical of most LDEF fibers. Figures 8,9 and 10 show similar plots for the current 'N-1 ', 'N-2' and 'N–3' samples. On all graphs, the vertical axis indicates the *increase* in the fibers' attenuation, in dB/km, at a given time after irradiation occurred. in almost all of the LDEF samples, the radiation induced attenuation was greater than the attenuation exhibited by the current samples. This was mainly duc to the fact that most of the off-the-shelf commercial fibers, manufactured at that time, contained dopants, such as phosphorus and germanium, in their core, All of the current fibers, on the other hand, were phosphorus free. Samples 'N- 1' and 'N–2' recovered within 24 hours, or less, and retained little attenuat ion, Surprisingly, the 'N- 3' sample, a radiat ion hardened fiber, cabled for space applications, retained much of its radiation induced attenuation at 820 nm. A similar test at 1300 nm 'shows a much improved performance, with the radiat ion induced loss decaying rapidly, and the fiber returning to almost pre- irradiat ion attenuat ion levels within several hours.

5. POLYMER AGING

The aging and degradation of polymers in spacecraft fiber optic cables is an important subject since their service conditions arc far from ideal. The polymer is usually subjected to a multitude of stresses, such as temperature extremes, light, atomic oxygen, ionizing radiation, and mechanical distortion. These stresses can result in both chemical, as well as physical changes in the polymer, leading to the gradual degradation of the material,

in comparison to the control samples, which remained in the lab, the externall y mounted LDEF flight fiber cables exhibited some small changes in their properties, mainly noticeable during handling The cables were somewhat harder and less flexible, while the fibers themselves were more fragile, requiring more care during their connector termination procedure. The internally mounted samples did not show any observable changes, compared to the control samples.

6. MICROMETEOROIDS

Micrometeoroids and space debris pose a significant risk to fiber cables which are exposed outside of the spacecraft structure, for example in tethered applications incorporate ing a fiber optic data link. The LDEF experiments provide some information which allows onc to estimate the risk to fiber cables deployed in low-earth orbit,

The four externall y mounted fiber cables in the JPL experiment, were located 90° from the ram direction. On average, the number of visible impact craters, having a diameter of greater than 0.1 mm, were 33 on the fiber mounting plates, 21 on the f iber cable sample itself, and 2 on the metal mounting clamps. A total of three impacts that left craters about 0.5 mm in diameter were detected on three different fiber cable samples, All four fibers, each 25 m long and exposed on onc side onl y, sustained no damage and were fully functional. The Air Force Phillips Lab fiberoptic experiment (LDEF Experiment No. M0004) exhibited a total of two craters about 0.5 mm in diameter on the fiber cables, which did nor affect the fibers, and onc larger crater, about 1.5 mm in diameter, which did cause damage to the fiber itself, rendering the link nom-operational, This experiment was located near the ram direction and had four surface mounted fiber cables, having a total length of 75 m[1].

7. DISCUSSION

Temperature: The LDEF experience showed a large range in performance under extremely hot and cold temperature conditions. The 'P-1' sample, in particular, withstood the cold temperature extremes much belter than other LDEF fiber samples, sustaining only a 4 dB/km loss at –55 "C. This fiber was coated with two layers of UV cured acrylate buffer, the inner layer having a low modulus and the outer layer having a higher modulus[12]. The two layer buffer, having an outside diameter of 0.5 mm, was placed in a hytrel tube of inside/outside diameter of 0.5/1.0 mm. The entire buffer structure was tight (net 100SC tube). l'hc fiber also had a relatively high numerical aperture (NA), which also favored lower temperature-induced microbending losses.

Wc feet that the buffer coating and the cable design itself play an important role in the fibers' temperature related performance. The current fiber samples, tested in this work, show that cable and buffer designs have been improved over the last decade. As seen in Table 3, all the 'N' samples had very low changes in light output at the temperature extremes, with most of them actually showing a decrease in loss. The commercial 'N--J' fiber cable sample, made with an acrylate buffer material, showed a tremendous improvement over its 'P-1' counterpart, The space qualified 'N- 3' sample, made with a pol yimide buffer material, actual] y had an increase in light output of 1.33 dB/km at -55°C. in applications in which the fiber is mounted inside a spacecraft, thereby]-educing, temperature extremes to the - 10°C to + 40°C range, an even better performance is expected.

Radiation: Although the initial damage mostly anneals out duc to thermal effects or to light (photobleaching), a residual increase in attenuation, influenced by impurities and dopants in the. fiber material, permanently remains in the fiber. Although all of the LDEF fiber samples were off--the-shelf products, available over ten years ago, some of the better samples, such as 'P- 1', could have performed satisfactorily in most spacecraft applications. The current Samples outperformed almost all of the LDEF f iber cables. The 'N-- 1' sample, an off-the-shelf, non- space qualified, product had a residual long-term radiation induced attenuation of only 0.6 dB/km-krad, which was almost five. times better than the 2.9 dB/km- krad exhibited by the 'P- 1' sample. The radiation hardened 'N-3' sample, on the other hand, had an unusually high residual attenuation of almost 5 dB/km-rad, at

820 mn, ycl exhibited an extremely low residual attenuat ion of about 0.08 dB/km–rad, at 1300 nm. With the emergence of radiat ion hardened fibers, which can be exposed to radiation doses an order of magnitude larger than the radial ion doses seen by the LDEF samples, applications requiring fiber lengths of at least 1 km, could be supported. If the fiber is shielded or applied inside a spacecraft, reducing the radiation exposure even more, increasingly greater fiber lengths and longer mission lifetimes will bc possible.

Polymer Aging: Although polymer aging is not one of the traditional mechanisms considered when looking at applications of fiber cables in spacecraft, long--term space exposure can change the properties of polymers used in cabling and connector materials, changing their mechanical and optical properties sufficiently to affect the fiber link performance. Chemical reactions, such as hydrolysis, UV photooxidation, thermal oxidation, pyrolysis and radiation all have the potential to cause polymer degradation[13]. The impact of polymer aging on fiber optic system performance can be felt primarily in the following ways: 1) crystallinity change in the buffer materials, resulting in microbending, 2) changes in modulus of buffering materials that might change the optical 1oss versus temperature behavior of the fiber, 3) changes in stiffness or dimension, adversely affecting the cement u sed in connector termination, or in attaching fiber pigtails to semiconductor chips, and 4) evolut ion of volat iles which might affect connector performance or might interfere with other equipment on a spacecraft,

Micrometeoroids: ln light of the. results of the LDEF fiber optic experiments, impacts on exposed fiber cables present a small, but serious, risk of system damage. It number and severit y of the micrometeoroid impact damage seems to also correlate with the direction of the surface with respect to the direction of motion of the spacecraft. In order to assess the risk in operating an exposed fiber optic link in low- earth orbit, the LDEF data was combined as follows.

Converting the number of impact craters into a probability of finding an impact, the result is 15111-2 of 0.5 mm craters and 1111-2 of 1.5 mm crate.rs for the combined JPL and Air Force fiber optics experiments. These results can be used to estimate the probability of failure of a completely exposed straight fiber optic cable, oriented perpendicular to the ram direction. The probability of an impact large enough to cause fiber breakage is 1 per kn-year, while the probability of impacts leaving a 0.5 mm crater, without breaking the fiber, is around 20 pcr kn-year.

8. CONCLUSIONS

The LDEF fiber optics experiments have shown that certain fiber optic cables can be used in space for prolonged periods of time, Of the items discussed, radiation and temperat urc effects arc the most important, with either onc of them having the potential to seriously affect the overall performance of the fiber optic system. Polymer aging and micrometeoroids arc of less significance, but should not be ignored. in general, the overall importance of these issue.s is application and mission length dependent. in applications requiring fiber optic link lengths of tens of meters, deployed inside a spacecraft, they may not be critical, Applicat ions requiting much longer exposed fiber lengths, operating in a large radiat ion dose environment, must carefully take into account temperature extremes and total mission radiation dose. in their design. Placing the fiber cables in a shielded or controlled environment, decreases the attenuation increase due to radiation and temperature extremes, while at the same time protecting the fiber cables from polymer aging effects and micrometeoroid impacts.

In comparing the current fiber samples to the original LDEF fiber cables, great improvements in performance during temperature and radiation exposure arc noticed, Short lengths (< 100 m) of todays commercially available, off-the-shelf, fiber cables, such as the 'N-1' sample, would probably perform adequately on short missions (< 5 years), if given modest protection. Other fiber cables, such as the 'N–3' sample, arc provided with buffering and jacketing materials which can withstand much greater temperature extremes, while also using fibers less affected by radiation. These ongoing efforts in developing buffer and jacketing materials, which arc less susceptible to temperature extremes, and in purifying the fiber core, thereby reducing radiat ion induced at tenuat ion, will eventually lead to the ideal "space qual ified" fiber needed for 15 to 20 year missions.

9. ACKNOWLEDGMENTS

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Table 1: LDEF Fiber Optic Cable Samples

CABLE No.	CORE/CLAD/ CABLE DIA.	CORE/CLAD. MATERIAL	BUFFER MATERIAL	TUBE/JACKET MATERIAL	STRENGTH MEMBER/ CABLE JACKET	FIBER NA	NOMNL ATTEN.	BAND WIDTH	CABLE LENGTH
	(µm/µm/mm)						(dOhm)	MHz-km)	(m)
P-1	100/140/3.0	PURE SILICA/ BOROSILICATE	ACRYLATE	HYTREL JACKET	KEVLAR/ POLYURETHANE	0.29	7.0	100	26
P-2	1 00/1 40/3.0	PURE GLASS/ HARD SILICA	POLYMER COAT/ UV CURED OUTER COAT	HYTREL JACKET	KEVLAR/ POLYURETHANE	0.24-0.30	8.0	20	26
P-3	200/230/2.5	PURE SILICA/ FLUOROHYDRO-CARBON	ACRYLATE SOFT COATING	ACRYLATE HARD COATING	KEVLAR/ URETHANE	0.3s	8.0		30
P-4	50/125/3.0	PURE SILICA/ BOROSILICATE	ACRYLATE		KEVLAR/ POLYURETHANE	0.21	6.0	200	26
c-1	50/1 25/3.0	PURE SILICA/ BOROSILICATE	ACRYLATE	HYTREL JACKET	KEVLAR/ POLYURETHANE	023	7.0	400	50
c-2	60/1 25/2.5	PURE SILICA/ BOROSILICATE	SILICONE	HYTREL JACKET	KEVLAR/ POLYURETHANE	0.72	6.0	1s0	60
c-3	10/125/3.5	PURE SILICA/ SILICA	HALAR 300	POLYESTER TUBE	FIBERGLASS/ POLYURETHANE				60
c-4	10W14W3.O	PURE SILICA/ BOROSILICATE	ACRYLATE		KEVLAR/ POLYURETHANE	0.30	7.0	20	68
C-S	200/375/2.3	PURE FUSED SILICA/ RTV SILICONE	RTV SILICONE	TEFZEL JACKET	KEVLAR/HYTREL	0.33	12.0	11	60
C-6	60/1 2*.1	PURE QUARTZ/ QUARTZ	POLYACRYLATE	NYLON LOOSE TUBE	KEVLAR/	0.20	4.0	200	60

Table 2: Current Fiber Optic Cable Samples

CABLE No.	CORE/CLAD/ CABLE DIA.	CORE/CLAD. MATERIAL	BUFFER MATERIAL	TUBE/JACKET MATERIAL	STRENGTH MEMBER/ CABLE JACKET	FIBER NA	NOMNL ATTEN.	BAND WIDTH	CABLE LENGTH
	(µm/µm/mm)						(dB/km) 850/1 301	MHz-km) 1330	(m)
N-1	6?5/125/2.9	SILICA:Ge/ SILICA:Ge	ACRYLATE	THERMOPLASTIC	ARAMID YARN/PVC	0.275	3.0/1 .0	160	100
t'-?	100/140/2.76	SILICA:Ge/ SILICA:Ge	ACRYLATE	POLYESTER ELASTOMER (SEMILOOSE)	TEFLON IMPLUG. NATED FIBERGLASS/ ETFE	0,29	10.0/8.0	100	60
N-3	100/140/2.11	SILICA:Ge/ SILICA	POLYIMIDE	FLUORONATED ETHYLENE PRO-PYLENE (FEP)	TEFLON IMPREG-NATED FIBERGLASS/ FLUOROCARBON	0.311	5.0/2.0	223	60

Table 3: Temperature/Radiation Induced Attenuation at 820 nm

CABLE NUMBER	TEMPERATURE INDUCED	RADIATION INDUCED	
	EXTRAPOLATED CHANGE IN OUTPUT AT -55°C/+70°C (dB/km)	LOSS INCREASE AT END OF EXPOSURE* (dB/km-krad)	RESIDUAL ATTENUATION INCREASE 10+6 SEC AFTER END OF EXPOSURE* (dB/km-krad)
P-1	-3 8/-2.0	12.0	2.9
P-2	- 52.0/+ 14.5	x.5	30.0
P-3	-19.3/-13.8	95.0	73.5
P-4	-30.0/+ 8.0	90.0	94.0
c-1	-17.3/+ 0.6	94.0	94.0
c- 2	- 23.5/+ 1.0	65.0	62.0
C-3	-6.9/+5.1	14.0	7.0
c-4	-36.8/+ 1.6	14.5	1.5
C-6	-24.7/+ 1.3	3.6	0 2
C-6	-71.4/- 3.7	103.0	48.0
N-1	+ 0.04/- 0.24	6 9	0.6
N-2	-0.46/+ 0.30	5.2	1.4
N-3	+1.33/+ 0.67	10.7 (0.9)"	4.9 (0.1)**

* 2 krad doso for 'P' and 'C' samples, 5 krad doso for 'N' samples, **at 130Cknm

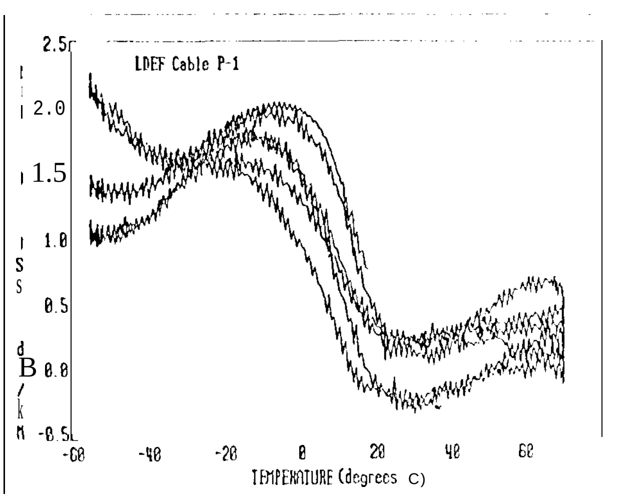

Figure 1. LDEF Cable P- 1
Temperature Induced Attenuation

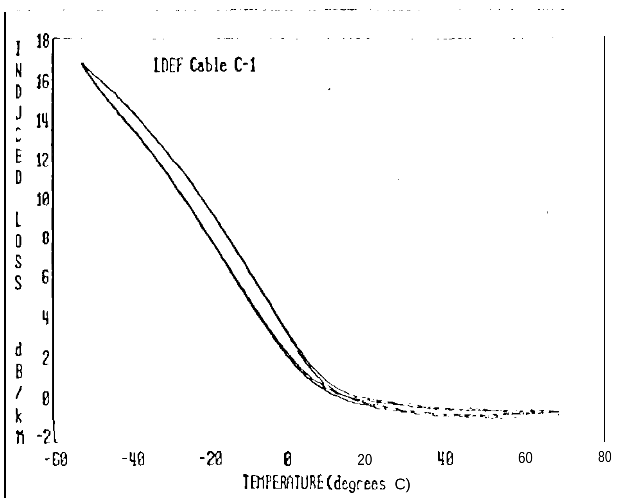

Figure 2. LDEF Cable C- 1
Temperature Induced Attenuation

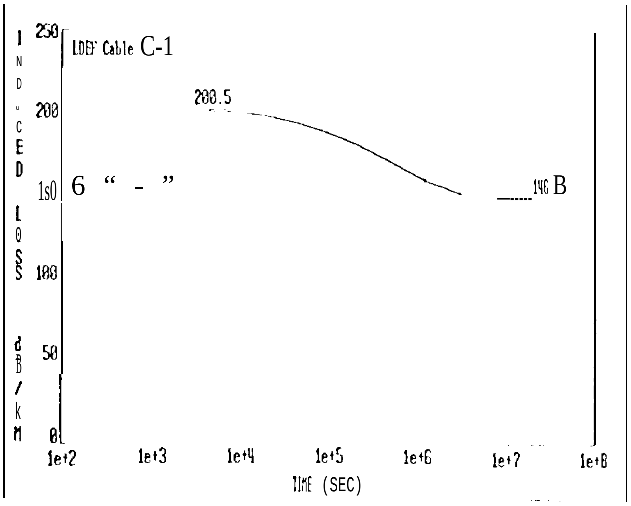

Figure 7. LDEF Cable C-1
Radiation Induced Attenuation

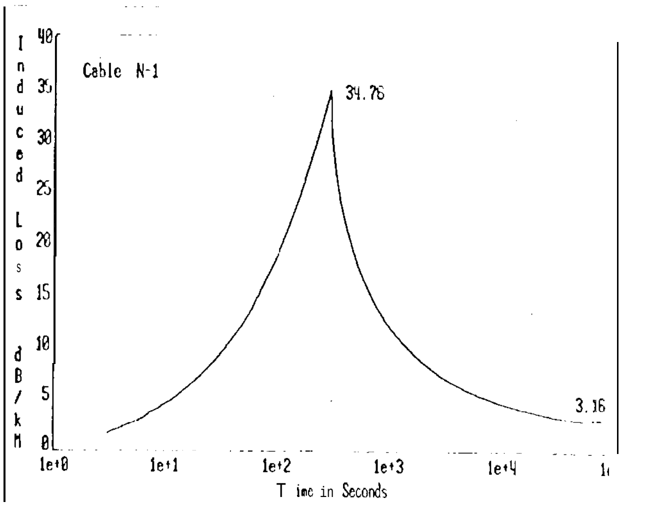

Figure 8. Current Cable N-1
Radiation Induced Attenuation

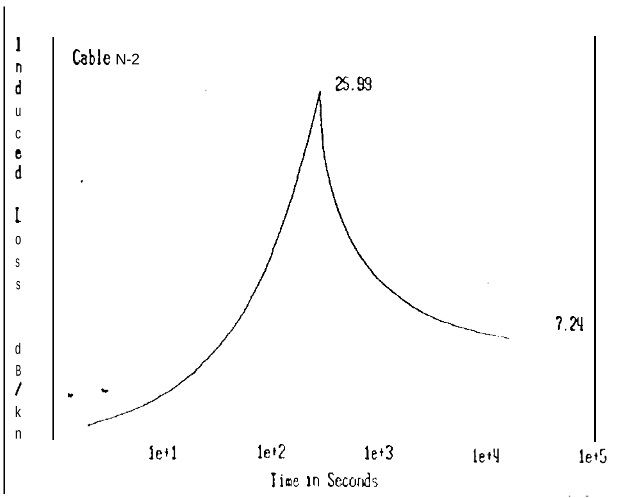

Figure 9. Current Cable N- 2
Radiation Induced Attenuation

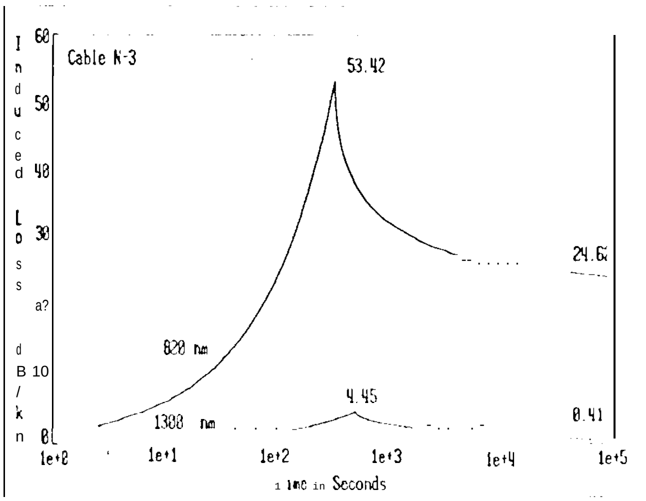

Figure 10. Current Cable N- 3
Radiation Induced Attenuation

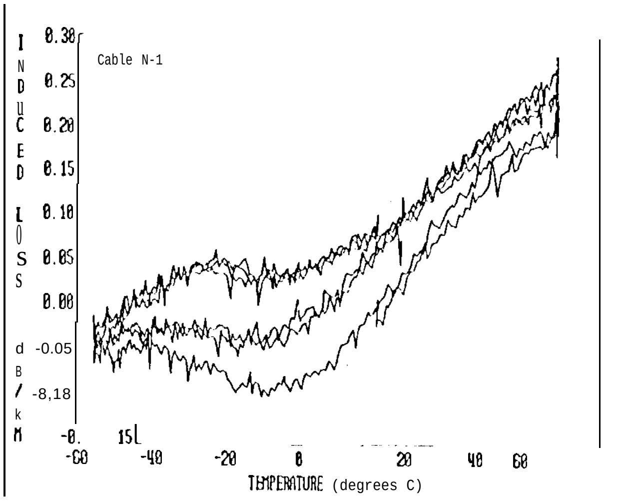

Figure 3. Current Cable N-1
Temperature Induced Attenuation

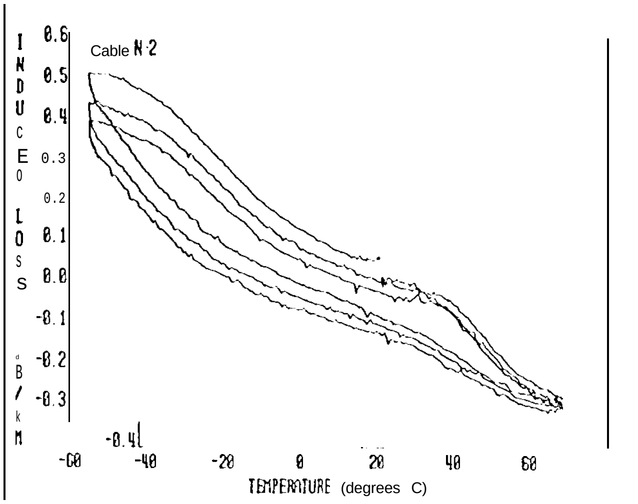

Figure 4. Current Cable N-2
Temperature Induced Attenuation

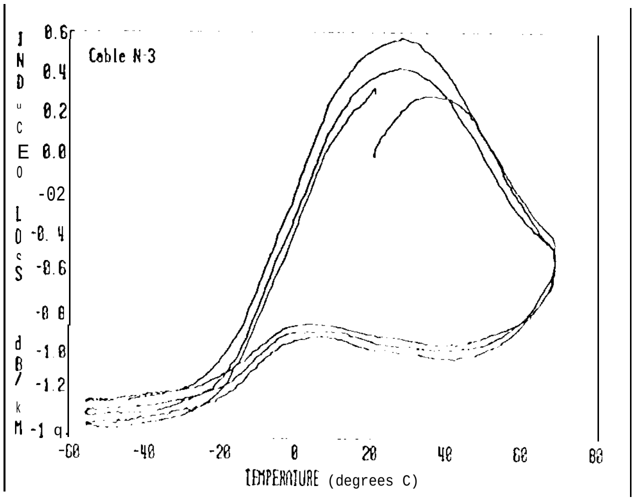

Figure 5. Current Cable N-3
Temperature Induced Attenuation

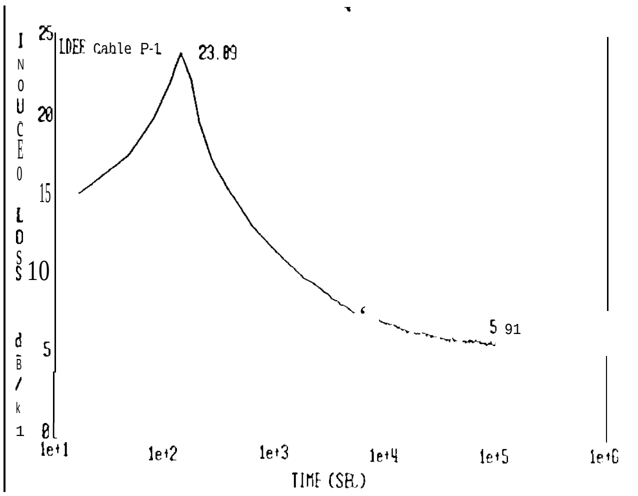

Figure 6. LDEF Cable P-1
Radiation Induced Attenuation